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(71) Applicant: Gerber, Arthur M.  
2864 Brannick Place  
San Diego CA 92122(US)

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(72) Inventor: Gerber, Arthur M.  
2864 Brannick Place  
San Diego CA 92122(US)

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(74) Representative: Strasse, Joachim, Dipl.-Ing. et al,  
Strasse und Stoffregen European Patent Attorneys  
Zweibrückenstrasse 17  
D-8000 München 2(DE)

(54) System and method for recording digital information.

(57) A digital recording medium formed of a thermoplastic substrate having a regular array of microscopic optically-alterable mirrors each supported by a mesa projecting from one surface. The parallel rows of the mirrors are the same distance apart as the mirrors in each row. A layer of transparent plastic over the mirrors provides dust protection. The medium can be formed from a single transparent thermoplastic substrate with an array of indentations in a first surface. The bottom of each indentation is coated with a reflective material. When viewed from the opposite surface of the substrate, the indentations become mesas.

Recording is by exposure to a laser beam that reduces the reflectivity of selected mirrors. After exposure to the recording laser beam, the mirrors retain enough reflectivity to be distinguishable from the intervening valleys. The mirrors serve as timing and tracking markers prior to and during recording, and during read-out. The area and location of each information bit is determined prior to recording: not as a result of the recording process. The mirrors are scanned diagonally across the rows that make up the array. Scanning is accomplished by reciprocating movement of the medium.

## 1 SYSTEM AND METHOD FOR RECORDING DIGITAL INFORMATION

2 Background of the Invention

## 3 Field of the Invention:

4 This invention relates to digital recording media and  
5 more particularly to high capacity recording media for  
6 optical recording and read-out.

## 7 Description of the Related Art:

8 Digital information has been recorded on many kinds  
9 of materials by a wide variety of processes. One widely  
10 used system magnetizes selected areas of a disk of magnetic  
11 material to represent the information to be preserved.  
12 Other approaches, used primarily when greater recording  
13 density is desired, include the use of a substrate coated  
14 with a material capable of being changed by selective  
15 treatment with a laser beam. For example, the substrate  
16 may have a reflective surface that is caused to have lower  
17 reflectivity in those areas where it is heated by a  
18 focused laser beam. Conversely, non-reflecting absorbent  
19 surfaces have been rendered reflective by the application  
20 of a laser beam as described in Optical Memory News,  
21 Sep.-Oct. 1984, page 14. The reflectivity of the surface  
22 may be altered by melting or deforming the surface or by  
23 actual evaporation of material from the surface. Most  
24 often, the medium is in the form of a disk and the information  
25 is recorded along a spiral track. The timing and

1 tracking information may also be recorded by a modulated  
2 laser beam following the spiral track.

3 U.S. Patents 4,214,249 to Kasai; 4,270,916 to Dil;  
4 4,379,299 to Fitzpatrick et al.; 4,314,262 to Reilly; and  
5 4,334,299 to Komurasaki et al. disclose media of the kinds  
6 referred to above.

7 The Dil Patent discloses recording on a disk having a  
8 grooved spiral and in which timing marks are recorded on  
9 the sloping walls of the grooves.

10 The Kasai patent discloses the recording of digital  
11 information by the selective exposure to a laser beam that  
12 causes deformation or evaporation of a layer composed of  
13 S, Se, Te, or chalcogenide compounds thereof. The rate of  
14 recording is limited by the heat conductivity of the  
15 medium.

16 The Fitzpatrick patent describes a digital writing  
17 process in which a film of semiconductor material, such as  
18 cadmium telluride, on a substrate of plastic such as  
19 methylmethacrylate or polycarbonate, is exposed to a  
20 recording laser beam that heats the plastic substrate to  
21 produce a pressurized gas bubble that bursts the overlying  
22 semiconductor leaving a pit or hole in the reflective sur-  
23 face that represents one bit of information. The rate at  
24 which information can be recorded is limited by the amount  
25 of heat required to cause the eruption and the heat con-  
ductivity of the recording medium.

1       The Reilly patent describes a recording medium formed  
2 by a thin continuous layer of metal in which bits of data  
3 are recorded by alterations produced with focused spots of  
4 laser light. A transparent dielectric coating is provided  
5 to increase the light absorption of the metal layer.

6       The Komurasaki patent describes a real-time monitor  
7 for use with a recording medium comprising a continuous  
8 film of metal such as bismuth, gold or chromium which is  
9 selectively melted or vaporized by a focused light beam to  
10 record one bit of information.

11      U. S. Patent 4,380,769 to Thomas et al. describes the  
12 recording of information by the thermal deformation of a  
13 continuous thin film of amorphous material carried by a  
14 plastic substrate. Individual depressions surrounded by  
15 sharply defined ridges are produced in the amorphous film.

16      U. S. Patent 4,334,233 to Murakami describes a dust-  
17 protecting shield over the substrate that minimizes infor-  
18 mation distortion that might otherwise occur because of  
19 dust particles on the recording medium.

20      U. S. Patent 4,428,075 to Hazel describes a prefor-  
21 matted disk in which synchronization marks are recorded in  
22 areas separate from the data recording areas. These  
23 tracking and timing marks are distinct from the altera-  
24 tions that represent bits of data and, to the extent they  
25 occupy space that could otherwise be used for digital  
storage, reduce the capacity of the disk.

1           The formation of arrays having microscopic relief  
2       patterns is known in the photographic field where such  
3       techniques are used to reduce variations in image density.  
4       U. S. Patents 4,366,299 to Land and 4,402,571 to Cowan et.  
5       al. discuss the formation of spaced discrete holes using  
6       a photoresist that is exposed twice to the interference  
7       patterns of two laser beams, one exposure being below the  
8       threshold for the development of the photoresist. Land  
9       also describes for photographic purposes the formation of  
10      peaks coated with silver as one step in formation of a  
11      silver halide coating. The structure proposed by Land  
12      does not lend itself to the recording of digital infor-  
13      mation.

14       U. S. Patent 3,019,124 to Rogers discloses a method  
15      of manufacturing photographic elements by applying a first  
16      light sensitive layer in a uniform thickness to a support,  
17      embossing the coated layer to form a relief impression  
18      having systematically arranged spaced elevated sections  
19      joined by depressed sections interspersed between them,  
20      and applying a second light sensitive layer having a dif-  
21      ferent spectral sensitivity to fill the depressions  
22      remaining in the surface to the level of raised sections.

23       U. S. Patent 4,362,806 to Whitmore describes a pho-  
24      tographic substrate comprising an array of microvessels  
25      that are filled with various photographic materials. The

1 object is to reduce lateral image spreading by providing a  
2 discontinuous recording substrate. The microvessels are  
3 separated only by minute distances that play no part in  
4 the recapture of information. Any appreciable thickness  
5 of the walls separating the microvessels detracts from the  
6 continuous image that is the object of the Whitmore  
7 disclosure. The recording is done over mass areas and the  
8 microvessel walls are used to prevent undesired lateral  
9 spreading of the photographic image. Whitmore suggests  
10 electronically scanning the photographic elements to read  
11 information in digital format. Whitmore also discloses  
12 modifying the microvessels by scanning with a laser beam  
13 to alter the character of selected microvessels by  
14 melting, sublimation or change in viscosity. The micro-  
15 vessels of Whitmore require subsequent photographic pro-  
16 cessing to provide optically readable information.

17                   Summary of the Invention

18                   A digital recording medium has discrete spaced indi-  
19                   vidually-alterable storage elements which, in one embodi-  
20                   ment, in the unaltered state, are tiny mirror surfaces,  
21                   sometimes called here "micromirrors", arranged in a  
22                   substantially regular array in a plane spaced from a  
23                   reference plane of a supporting substrate. Each micro-  
24                   mirror is supported by a mesa extending from the substrate  
25                   so that the micromirrors are separated by valleys or

1 indentations between the mesas. Each micromirror is indi-  
2 vidually optically alterable to store one or more bits of  
3 information. The substrate may be protected from con-  
4 taminates by a layer of transparent material of substan-  
5 tial thickness that minimizes the effect of dust par-  
6 ticles. The array of micromirrors is arranged to be  
7 scanned by a recording device and subsequently, without  
8 further processing, by a reading device.

9 Information is recorded by causing a change in the  
10 reflectivity of the selected micromirrors, for example, by  
11 subjecting the surface of each selected micromirror to an  
12 infrared light beam of sufficient intensity to materially  
13 reduce the reflectivity of the mirror. Each micromirror,  
14 by having one of two or more levels of reflectivity,  
15 becomes a depository for one or more bits of digital  
16 information.

17 The regular spacing of the array of micromirrors  
18 enables them to serve both as tracking and timing markers  
19 prior to and during recording and read-out. In effect, the  
20 medium itself acts as an optical encoder for the scanning  
21 device. This arrangement permits variations in the  
22 scanning velocity, a particular advantage when recipro-  
23 cating scanning procedures are used. The micromirrors may  
24 be used to control the scanning path, both for recording  
25 and read-out, by centering the beam along the path of  
maximum reflection.

1       The use of an array of regularly spaced discrete  
2       reflective micromirrors makes it possible to test the  
3       recording medium for defects prior to recording and  
4       authenticate its quality. In a practical way, this elimi-  
5       nates the need for monitoring the recording process  
6       because the chance of failing to record on a mesa having  
7       the required level of reflectivity is small.

8       The reduction in reflectivity of exposed micromirrors  
9       results from the absorption of sufficient energy to change  
10      the mirror coating itself or to distort the thermoplastic  
11      mesa supporting the mirror. The reflectivity of the  
12      recorded micromirrors preferably is not reduced to zero,  
13      but rather only enough that it can be readily  
14      distinguished as a recorded micromirror, the reflectivity  
15      of the recorded micromirror remaining greater than that of  
16      the valleys separating the micromirrors.

17      In another embodiment, the micromirrors are formed on  
18      the bottom surfaces of spaced indentations in a first sur-  
19      face of a sheet of clear substrate. Viewed from the  
20      second surface of the substrate, the indentations become  
21      mesas supporting the micromirrors. The recording and  
22      reading light beams are focused on the micromirrors  
23      through the second surface of the substrate.

24      In a preferred embodiment, the recorded medium is  
25      moved linearly along a full row of micromirrors, while a

1 small transverse oscillation of the read-out light beam  
2 maintains the lateral position of the recorded medium such  
3 that the read-out beam on the average, tracks the approxi-  
4 mate center of the row of mirrors being scanned. At the  
5 end of each linear scan, from end to end of the row of  
6 micromirros, the recorded medium is moved laterally one  
7 row and then moved linearly in the opposite direction. The  
8 arrangement of the micromirrors permits a wide choice in  
9 the selection of a particular read-out procedure.

10 Brief Description of the Drawing

11 Figure 1 is an enlarged diagrammatic top view of a  
12 small section of a recording medium embodying the  
13 invention;

14 Figure 2 is a sectional view along line 2-2 of Figure  
15 1;

16 Figure 3 is a partial perspective view of the  
17 recording medium shown in Figures 1 and 2;

18 Figure 4 is a reproduction of a scanning electron  
19 micrograph of the recording medium of Figures 1-3 at a  
20 magnification of 10,000X;

21 Figure 5 is a reproduction of a scanning electron  
22 micrograph of an embossed layer of PVC for use in fabri-  
23 cating the recording medium;

24 Figure 6 is a reproduction of a photograph of a video  
25 image of the medium taken from a video screen at a magni-  
fication of 1,750X;

1       Figure 7 shows a section of the medium of Figures 1-3  
2       including a transparent protective shield and in which a  
3       filler is placed in the valleys between the mirrors:

4       Figure 8 is a partial sectional view of another  
5       embodiment of the recording medium in which the protective  
6       shield and the substrate are formed integrally from a  
7       single sheet of plastic;

8       Figure 9 shows diagrammatically a source of laser  
9       light and the associated optics and detectors for  
10      recording on and reading from the medium;

11      Figure 10 illustrates diagrammatically a preferred  
12      scanning sequence for both recording and read-out; and

13      Figure 11 illustrates the use of the micromirrors for  
14      tracking during recording and read-out.

15      Description of the Preferred Embodiments

16      The drawings are not to scale and various elements  
17      have been exaggerated for purposes of illustration. In  
18      the various figures, similar elements are indicated by the  
19      same numerals or by the same numerals followed by an iden-  
20      tifying letter suffix.

21      As illustrated by Figures 1-3, a recording medium,  
22      generally indicated at 2, in this example, is in the form  
23      of a rectangular plastic card about 2 by 3.5 inches which  
24      is capable of recording more than 800 megabits of digital  
25      information. The medium comprises a substrate or base

1 element 4 having an array of uniformly spaced micro-  
2 mirrors 6, each supported by a minute projection or mesa 8  
3 extending from one surface of the substrate 4. The pro-  
4 jections 8 are integrally formed as part of the substrate  
5 4, which may be formed of thermoplastic material, and are  
6 separated by valleys, generally indicated at 10.

7 The projections or mesas 8 which support the micro-  
8 mirrors 6 serve two functions: to provide thermal isola-  
9 tion between adjacent mirrors and to provide a light sink  
10 between the mirrors in the form of the valleys 10. The  
11 height of the projections 8 above the substrate 4 is not  
12 critical and is typically between 0.5 and 2.5 micrometers.  
13 The projections 8, in this example, are arranged in the  
14 array to provide one storage element for each two micro-  
15 meters along each row of mirrors.

16 The thickness of the substrate 4 is not critical but  
17 may be of the order of 100 or more times the height of the  
18 mesas 8. The mirrors 6, which lie in a common plane, are  
19 of material capable of reflecting laser light. Each  
20 micromirror is of sufficient size and flatness to function  
21 as an effective mirror at the frequency of light being  
22 used to read the data from the medium. The mirrors may be  
23 formed by coating the tops of each mesa 8 with a layer of  
24 reflective material capable of absorbing sufficient energy  
25 to permit a low power laser beam to reduce significantly

1 the reflectivity of the micromirror with an exposure of  
2 less than about one microsecond. The preferred mirror  
3 coating is a composite formed of gold and silicon dioxide.  
4 The mirrors 6 should be as flat as possible and the sur-  
5 face variations should be limited to a fraction of a wave-  
6 length of the incident light, for example, from one-fifth  
7 to one-tenth of a wavelength. For the present purposes, a  
8 mirror capable of reflecting 20-25% or more of the inci-  
9 dent light to be used for readout is defined as a "flat  
10 mirror". Each micromirror is capable of immediately  
11 detectable alteration, for example, by exposure to a  
12 source of focused energy, such as a laser beam, by which  
13 is meant the alteration takes place substantially  
14 immediately upon such exposure and may be detected without  
15 further processing such as is required in photographic and  
16 other indirect processes.

17 Preferably, the micromirrors 6 form a regular array  
18 as illustrated by Figure 1. By a regular array is meant  
19 an array in which the storage elements are equally spaced  
20 in parallel rows that are separated by a distance equal to  
21 the distance between adjacent storage elements in the  
22 rows. With this arrangement, the medium can be tested for  
23 defects prior to recording by scanning the surface of the  
24 medium with a non-destructive laser beam and measuring the  
25 reflectivity from each micromirror. The reflective and

1 absorptive capacity of the micromirror is a function of  
2 the amount of coated material on the mesa, therefore, if  
3 each micromirror is confirmed for reflectivity, the medium  
4 can be certified for recording with a high degree of  
5 assurance that the recording will be accurate. During  
6 this pre-test, the physical position, as well as the  
7 reflectivity, of each micromirror is verified. This may  
8 be done by any desired mode of scanning in which the  
9 distance between micromirrors is verified, as by a  
10 counting device related to the speed of the beam scan.

11 Each micromirror 6 represents one bit of information.  
12 Note that the size of each bit of information is deter-  
13 mined prior to recording: it is not the recording device  
14 that determines either the position or size of the infor-  
15 mation bits. With this arrangement, the micromirrors 6  
16 themselves provide the tracking guides for pre-testing,  
17 recording, and read-out. The data can be packed with maxi-  
18 mum density because no allowance is required for  
19 variations in laser spot size during recording. The  
20 tolerances permitted in the area of the focus of the laser  
21 beam at the plane of the mirrors are thus greater than in  
22 those arrangements where the position and size of each  
23 recorded bit is determined by the action of the laser  
24 beam. The maximum surface dimension of each micromirror  
25 is preferably between 1 and 2.5 micrometers and the mini-

1       mum dimension should not be less than the wavelength of  
2       the light being used for reading. For special applica-  
3       tions, the mirror size may be less than one micrometer or  
4       substantially greater than 2.5 micrometers. For most  
5       applications, where density of recording is important,  
6       the area of the micromirror preferably is between 0.7 and  
7       about 5 square micrometers. It is preferred that the  
8       distance between the mesas 6 be not significantly less  
9       than the maximum surface dimension of the micromirrors.  
10      The reflecting area of the micromirrors 6 may be round,  
11      square, rectangular or any other desired shape. It is  
12      convenient, however, to provide a regular array of  
13      generally round reflecting surfaces equally spaced in  
14      parallel rows, such as result from the example set forth  
15      below. Each micromirror preferably has an original  
16      reflectivity of at least 20% of the particular laser light  
17      being used. After exposure to the laser beam to destroy  
18      the reflectivity, the reflection preferably is signifi-  
19      cantly less than 20% or at least significantly less than  
20      the reflectivity of the original mirror surface.

21      In one system, preferred for many typical applica-  
22      tions, the round micromirrors of one micrometer diameter  
23      are spaced one micrometer apart and a recording laser beam  
24      is arranged to scan the mirrors at a speed of about two  
25      meters per second to record data at a one megabit/second  
       rate. If a higher data rate is desired, a faster scanning

1 speed can be used. The micromirrors preferably are spaced  
2 as closely as possible in the array, for maximum storage  
3 capacity, but the dimensions of each mirror must be large  
4 enough to permit it to function as a mirror at the wave-  
5 length of light being used and the micromirrors must be  
6 separated by a distance great enough that neither the  
7 recording or read-out laser beam can overlap two micro-  
8 mirrors.

## 9 EXAMPLE

10 The following is an example of the steps in the  
11 preparation of the recording medium embodying the  
12 present invention: A photoresist relief pattern  
13 comprising a square array of flat bottoms with  
14 tapered peaks, with center-to-center spacing of about  
15 2 micrometers (see Figures 4, 5 and 6) was prepared  
16 as follows. Positive photoresist (Shipley AZ-1450J,  
17 manufactured by Shipley Company, Inc. Newton,  
18 Massachusetts) was spin coated on a glass plate to a  
19 thickness of several micrometers. The plate was then  
20 exposed to an argon laser interference pattern using  
21 a glass prism to split the beam and to recombine the  
22 two halves, thus forming a series of spaced parallel  
23 interference lines at the photoresist target. The  
24 exposure was through the glass plate so the greatest  
25 exposure was at the bottom of the layer of the photo-  
resist.

1           After a three-minute exposure, the plate  
2        was rotated 90 degrees and exposed a second time, as  
3        described by M. T. Gale in Optics Communications,  
4        Volume 18, No. 3, August 1976, page 295. The plate  
5        was then developed for twenty seconds in Shipley  
6        developer. Figure 4 is a reproduction of a scanning  
7        electron micrograph, at a magnification of 10,000X,  
8        of the photoresist pattern, tilted at an angle of  
9        about 45°. This micrograph shows partly etched saddle  
10      points between adjacent peaks, indicating that each  
11      exposure was above the threshold for development of  
12      the photoresist. It shows also that at the inter-  
13      section of the lines, etching of the photoresist  
14      extends to the surface of the glass plate. The flat  
15      surfaces thus created are important because they  
16      will define the flat substrate of the reflective  
17      micromirrors of the optical recording medium.

18       A nickel mold was made from the photoresist  
19      plate, prepared as above. This process is described  
20      in National Geographic, March 1984, page 373. A  
21      second generation nickel electroform was made from  
22      the original nickel master. The second generation  
23      nickel had contours corresponding to those of the  
24      photoresist plate and served as a stamper to repro-  
25      duce the pattern by embossing sheets of plastic.

1           An array of flat-topped plastic mesas was pro-  
2         duced by embossing a sheet of PVC plastic with the  
3         nickel stamper, described above, in a Carver  
4         Laboratory press, Model C, manufactured by Fred C.  
5         Carver, Inc., Menomonee Falls, Wisconsin. The nickel  
6         stamper was placed, contoured side up, on a sheet of  
7         lead on the lower stage of the press. A sheet of 10  
8         mil thick glossy black PVC plastic, obtained from  
9         Ridout Plastics, San Diego, California, was placed  
10       over the nickel stamper. The press was pumped to a  
11       pressure of 20,000 pounds and the lower heating unit  
12       was raised to a temperature of 250 degrees Farenheit.  
13       The heater in the upper platen was not energized  
14       while the heat from the lower unit penetrated the  
15       lead, nickel and plastic. When the thermometer in  
16       the upper platen read 200° F., the lower heater was  
17       turned off and the 20,000 pounds pressure was main-  
18       tained during cooling. When the temperature in the  
19       upper unit had dropped to 150° F., the pressure was  
20       released and the PVC was peeled from the nickel  
21       stamper. A bright diffraction pattern was visible on  
22       the embossed PVC. Figure 5 is a reproduction of a  
23       scanning electron micrograph of the embossed PVC at a  
24       magnification of 10,000X tilted at an angle of about  
25       45°.

1           A reflective material was then coated on the  
2         embossed surface of the PVC. This material was chosen  
3         to be both reflective enough to permit identification  
4         as a micromirror by an optical reading device and  
5         also capable of absorbing sufficient laser energy to  
6         melt or cause distortion of the plastic substrate  
7         during data recording. The preferred material is a  
8         metal and ceramic composite of gold and silicon  
9         dioxide. Such materials, known as cermets, have been  
10        used for thin film resistors and in light absorbing  
11        applications such as solar collectors. The  
12        Au-SiO<sub>2</sub> system is described in the Handbook of Thin  
13        Film Technology, McGraw-Hill, 1983, chapter 18, page  
14        21.

15           The cermet layer, coated on glossy clear  
16         polyester, has about four times greater absorbancy at  
17         830 nm than a pure gold layer on the same substrate.  
18         The cermet is also significantly more sensitive to  
19         alteration of reflectivity by laser light. A pure  
20         gold layer showed no response to pulses of several  
21         microseconds, at a power level of about 5 milliwatts.  
22         Under the same conditions, the cermet coating showed  
23         significant changes in reflectivity in response to  
24         pulses of less than one microsecond.

1           Finally, cermet was sputter coated on the  
2 embossed PVC described earlier. This storage medium  
3 showed visible changes in reflectivity at pulse dura-  
4 tions of less than 0.3 microseconds at the same 5  
5 milliwatt power level.

6           Figure 6 is a reproduction of a photograph of a  
7 sample of the recording medium comprising an array of  
8 individually alterable micromirrors of  
9 Au-SiO<sub>2</sub> on embossed PVC plastic. The photograph was  
10 from a TV monitor attached to an optical system pro-  
11 viding a magnification of about 1750X on the screen.  
12 Some of the micromirrors in a row near the bottom  
13 have been exposed to a 0.5 microsecond pulse from an  
14 830 nm diode laser, at a power level of about 5  
15 milliwatts. The darkened spots are clearly visible  
16 as areas of significantly lower reflectivity in  
17 response to the laser pulses.

18  
19           In this test, the response to the recording laser  
20 beam was only along the rows of micromirrors, not between  
21 them. If only a portion of a micromirror is exposed to  
22 the laser beam, the entire micromirror will still melt or  
23 be distorted, although somewhat more slowly. These  
24 properties are especially advantageous in optical data  
25 recording because the recorded spot size and location is

1 less sensitive to variations in the laser spot size and  
2 alignment.

3 In reading a previously recorded area of the medium,  
4 it is desirable to be able to distinguish between three  
5 levels of illumination: the level represented by an  
6 untreated micromirror retaining its original reflectivity,  
7 the level represented by a micromirror that has been  
8 treated by the laser beam to destroy its reflectivity, and  
9 the reflectivity represented by the valleys 10 between the  
10 mesas 8. The areas between the mesas have no reflecting  
11 surface in the plane of the micromirrors 6, so that the  
12 reflection is reduced by dispersion of the beam at posi-  
13 tions beyond the focal point of the beam. The untreated  
14 areas of the medium 2 between the mesas will also have an  
15 inherently lower reflectivity than the micromirrors 6 even  
16 though some of the sputtered mirror coating material is  
17 deposited in the valley areas. Generally, therefore, it  
18 is not desirable to eliminate all reflectivity of the  
19 micromirrors 6, but to reduce it only enough to make it  
20 readily distinguishable from the untreated micromirrors.  
21 This allows recorded micromirrors to continue to serve as  
22 tracking and timing markers. In this example, the  
23 unaltered micromirrors have a reflectivity greater than  
24 20% at 830 nm and a laser power of about 3.2 nanojoules  
25 per square micrometer is sufficient to reduce the reflec-

1 tivity of the mirror coating by the desired amount. Other  
2 kinds or quantities of mirror coatings can be used that  
3 require higher recording energy, but it is preferable  
4 that the micromirror be destroyed by exposure to focused  
5 energy no greater than 200 nanojoules per square micro-  
6 meter.

7 It is important to provide a mirror surface that is  
8 relatively immune to oxidation or discoloration or dulling  
9 from other causes. It is important also, to provide a  
10 surface that is affected only minimally by dust or other  
11 contaminates. For those reasons, a layer of transparent  
12 material, generally indicated at 12 in Figure 7, is posi-  
13 tioned over the surface of the mesas 8. This layer, which  
14 may be formed of polyester, polycarbonate or other  
15 transparent plastic, is in contact with the micromirrors 6  
16 and is of substantial thickness (100 or more times the  
17 height of the mesas 6) so that, during recording and read-  
18 out by a laser beam focused on the micromirrors 6, the  
19 converging laser beam covers a significant area at the  
20 point where it enters the layer 12 and so minimizes the  
21 effect of a dust particle on the surface of the layer 12.

22 A filler 14, which may be a liquid such as oil, fills  
23 the valleys 10 and displaces any air that would otherwise  
24 be trapped between the micromirror surfaces and the layer 12.  
25 The liquid is preferably selected with an index of refrac-

1      tion near that of the plastic from which the layer 12 is  
2      formed to avoid any undesirable reflection of the laser  
3      beam. The filler 14 may remain as a liquid or it may be  
4      composed of a liquid plastic accompanied by a catalyst so  
5      that after the filler is in position the plastic solidi-  
6      fies. Alternatively the filler may be a UV curable  
7      polymer. With any of the filler compositions, it is  
8      desirable to add an infrared absorbing dye to the filler  
9      to further reduce any reflection from the valleys 10.  
10     Such dyes are well known in the prior art.

11     In general, the recording of data by altering the  
12    reflectivity of selected micromirrors results in each  
13    micromirror having only one of two possible states, that  
14    is, the micromirror reflects the incident light as a  
15    mirror or has a reflectivity below some predetermined  
16    level and is not considered to be a mirror. The density  
17    of information storage can be increased by providing for  
18    additional levels of reflectivity. For example, each ori-  
19    ginal micromirror 6 can be constructed to have a reflec-  
20    tivity of 40-45% at the frequency of the laser beam used  
21    for readout. A first level of intensity of the laser  
22    recording beam may be adjusted so that during the time of  
23    recording on one micromirror, the reflectivity is reduced  
24    to between 25% and 35%. To record another state, the  
25    intensity of the recording laser beam is increased suf-

1 ficiently that during the time of exposure the reflect-  
2 tivity is reduced to between 10% and 20%. A single micro-  
3 mirror can thus be used to store any one of three infor-  
4 mation indicia: (1) the mirror retains full reflectivity,  
5 that is, between 45% and 55%; (2) the reflectivity is  
6 between 25% and 35%; and (3) the reflectivity is between  
7 10% and 20%. The valleys 10 should have a reflectivity  
8 substantially less than 10% to permit even the micro-  
9 mirrors with minimum reflectivity to be used as timing and  
10 tracking guides.

11 In an alternative embodiment, the recording medium  
12 and the overlying plastic protective sheet are fabricated  
13 as an integral structure. As illustrated by Figure 8, the  
14 stamper used to form the medium 2a is the reverse of the  
15 one used to form the medium of Figures 1-3. In this  
16 instance, the mesas 8a are formed as depressions in a  
17 first surface 16 of a substrate 4a formed of clear ther-  
18 moplastic. The micromirrors 6a are formed by exposing the  
19 surface containing the indentations to the sputtering  
20 action of the mirror coating. The micromirrors 6a are  
21 therefore formed on the flat surfaces at the bottoms of  
22 the indentations. However, viewed from the opposite side,  
23 in the direction of the arrow 18, the indentations appear  
24 as mesas with the mirror coating on the flat tops.  
25

1       The micromirrors 6a are exposed to the recording and  
2 reading laser beams, in the direction of the arrow 18,  
3 through the plastic substrate 4a. With this arrangement,  
4 the micromirrors 6a are in intimate contact with substrate  
5 material providing superior protection of the reflecting  
6 surfaces from contamination. One additional advantage of  
7 this construction is that, in the process of fabrication,  
8 reflective material that is inevitably sputtered onto the  
9 exposed surface 16 of the substrate 4a, which forms the  
10 bottoms of the valleys 10a, may be completely removed by  
11 abrading. The bottom surface of the substrate 4a between  
12 the indentations may be provided with a layer of light  
13 absorbent material thereby rendering the valleys 10a  
14 between the micromirrors substantially non-reflective.  
15 The plastic material of the substrate 4a now replaces the  
16 layer 12 that is a separate entity in the earlier embodi-  
17 ment. The plastic is continuous from the surface exposed  
18 to the laser beam to the bottom of the valleys 10a at the  
19 surface 16 with no disruptive reflections resulting from a  
20 change in the index of refraction.

21       One scanning procedure for recording on and reading  
22 from either of the embodiments of the medium 2 and 2a is  
23 illustrated by Figures 1 and 9. A source of coherent  
24 light, such as a diode laser 22, produces a beam 24, that  
25 is first made more uniform by a collimating lens and an

1 anamorphic prism, both indicated diagrammatically at 16,  
2 and then is focused through an objective lens 32 onto the  
3 micromirrors 6. The maximum dimension of the beam in the  
4 plane of the mirrors, indicated by the broken line 28, is  
5 preferably no greater than the cross-sectional area of  
6 each individual mirror, and in any event small enough to  
7 distinguish one micromirror from any adjacent micromirror.  
8 The same optical system is used for both recording and  
9 reading. The laser light reflected from the micromirrors  
10 is directed by a beam splitter 20 to an optical detector,  
11 generally indicated at 36.

12 One method for scanning the medium 2 is to cause the  
13 laser beam to traverse one row of micromirrors from one  
14 end of the medium 2 to the other. At the end of each row,  
15 the laser beam is caused to move to the next row of micro-  
16 mirrors and to scan that row in the opposite direction.  
17 As illustrated in Figure 1, a first row of micromirrors is  
18 scanned along line "a" from one end of the medium to the  
19 other. The scanning beam is then moved sideways to the  
20 next row and scans along line "b" in the reverse direc-  
21 tion. The beam is then again moved sideways and the  
22 micromirrors scanned along line "c". A preferred proce-  
23 dure, however, is to scan the micromirrors diagonally as  
24 illustrated by Figure 10 which provides an improved signal  
25 to noise ratio by increasing the distance between suc-

1       cessive micromirrors. The equally spaced rows of micro-  
2       mirrors that make up the regular array are represented by  
3       the broken lines "d" and "e". The scanning track of the  
4       laser beam 24, however, is successively along lines "f",  
5       "g" and "h" which are diagonal with respect to the  
6       parallel rows of micromirros, such as "d" and "e", forming  
7       the regular array. At the end of row "f", the scanning  
8       motion is interrupted and moved sideways in the direction  
9       of the arrow "j" to place the row "g" in scanning posi-  
10      tion. The laser beam then scans that row in the reverse  
11      direction along the line "g". This process is repeated to  
12      scan the entire series of rows over the entire surface of  
13      the medium. An end-of-row code is pre-recorded on each  
14      row and is read by the recording and reading systems to  
15      cause the scan to move to the next row of micromirrors at  
16      the appropriate point.

17       The scanning movement along the rows may be  
18       accomplished by moving either the entire laser and optics  
19       assembly or by moving the medium 2. In this example,  
20       because the mass of the medium 2 is only a fraction of  
21       that of the laser-optics assembly, there is substantial  
22       advantage in moving the medium. The reciprocating  
23       scanning action, which results in variations in the  
24       scanning velocity, is made practical by the regular  
25       arrangement of the micromirrors which can be used to

control the timing both during recording and read-out.

The transverse movement, to move the beam from one row of micromirrors to the next, is preferably accomplished by a sideways movement of the laser 22 and the associated optics at the end of the scanning of each row of micromirrors. The sideways movement may also be accomplished by movement of the medium, by deflection of the laser beam, or by a combination of the two. For example, the laser beam may be deflected, by means well known in the art, to accomodate the scanning of a pre-selected number of rows and then the medium moved sideways by a similar number of rows while the beam deflection is returned to its original position.

During the scanning, the position of either the laser beam or the medium 2, or both, are controlled by the use of the micromirrors as tracking guides. During the scanning of each row of micromirrors, the beam 14 is caused to oscillate transversely, at a frequency much lower than the data rate, by a galvanometer-actuated mirror, or other means well known in the art, for a distance at the point of focus somewhat less than the distance across one micromirror. The transverse sweep of the scanning action is indicated by the broken lines 38 and 42 in Figure 11 as the scan proceeds along the centerline "k". The magnitude of the transverse scan depends

1 upon the size of the micromirrors, the size of the  
2 scanning spot, and the distance between adjacent micro-  
3 mirrors. The intensity of the reflected light is averaged  
4 by a tracking control mechanism, which forms part of the  
5 optical detector 36, over a substantial number of micro-  
6 mirrors before changing the direction of oscillation, in  
7 order to improve the tracking precision. The tracking  
8 control mechanism maintains the beam 24 centered on the  
9 row of micromirrors being scanned. If the average inten-  
10 sity of the reflected beam when it is deflected, say, to  
11 the right, as diagrammatically illustrated at 44, is less  
12 than the average intensity when deflected an equal  
13 distance in the opposite direction, the beam 24 is  
14 adjusted toward the left to move it nearer the center line  
15 of the micromirrors. If desired, the area of the beam 24  
16 in the focus plane may be made slightly larger than the  
17 reflecting area of one micromirror, so long as it is small  
18 enough that it cannot encompass any substantial fraction  
19 of two mirrors at the same time, so that it can detect the  
20 reflectivity of each micromirror despite small misalign-  
21 ment of the read-out beam relative to the centerline of  
22 the row of micromirrors being scanned.

23

24

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1        Prior to recording, the medium 2 is scanned by the  
2        laser beam 24 at low intensity to determine whether all or  
3        substantially all of the micromirrors have the requisite  
4        reflectivity. After the medium has been certified as free  
5        from defects, or the defects "fenced off" as described  
6        below, the permanent recording is made by the laser beam  
7        24 which has a first level of intensity sufficient to  
8        enable the optical detector 36 to determine the presence  
9        of a reflecting micromirror 6 on the surface of a mesa 8,  
10       and a second level of intensity great enough to destroy  
11       the reflectivity of the micromirror at which it is  
12       directed. The intensity of the laser beam 24 is modulated  
13       as the recording is made to destroy the reflectivity of  
14       the mirrors in accordance with the information to be  
15       recorded.

16       The laser beam 24 operates at its low or reading  
17       intensity until the detector 36 indicates the beam is  
18       focused on a micromirror. If the digital information to  
19       be recorded indicates that particular micromirror is to be  
20       destroyed, the laser beam is pulsed to its higher  
21       recording intensity for a period of one microsecond or  
22       less, but long enough to destroy the micromirror. If that  
23       particular micromirror is not to be destroyed, the laser  
24  
25

1 beam passes over it at the lower non-destructive intensity  
2 leaving the reflectivity of the micromirror unchanged.

3         By destruction of the reflectivity is meant a  
4 lowering of the reflectivity by an amount sufficient that  
5 the optical detector 36 can determine the difference  
6 between a micromirror that has been exposed to the laser  
7 beam 24 at recording intensity from one that retains its  
8 original reflectivity.

9         If the examination of the medium prior to recording  
10 indicates relatively few defects, the rows of micromirrors  
11 containing defects can be "fenced off", that is, the par-  
12 ticular rows containing defects are marked with a special  
13 code that causes the scanning mechanisms used in both  
14 recording and reading to jump immediately to the suc-  
15 ceeding row and omit scanning the defective areas of the  
16 medium. So long as the number of defects is limited, the  
17 loss in recording capacity is not significant. In  
18 addition, error-correcting codes which, in effect, record  
19 data in a redundant manner in different areas can be used  
20 to overcome defects in the recording medium.

21         In the examples detailed here, the medium is in the  
22 form of a small rectangular card, no more than 10-15 mils  
23 thick, well suited for reciprocal scanning modes.  
24 However, the recording array may be in the form of a drum,  
25 disk or tape and the scanning mode may be either recipro-

1 cating or continuous. The recording medium may be formed  
2 as a flat medium and then secured to a rotatable drum, or  
3 otherwise altered in shape, for recording and read-out.  
4 The reference plane of the medium, that is, one of the  
5 exposed surfaces, is considered to be parallel with the  
6 plane of the micromirrors even though both surfaces may be  
7 curved so long as the two planes are the same distance  
8 apart at all points.

9

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CLAIMS:

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1       1. A system for recording digital information comprising  
2            a recording medium having  
3              a substrate, and  
4              a substantially regular array of spaced,  
5            discrete, immediately detectable alterable storage ele-  
6            ments, each capable of recording at least one bit of digi-  
7            tal information,  
8              a laser beam source capable of sufficient intensity  
9            to immediately alter a storage element of said medium  
10          exposed to said beam,  
11          scanning means arranged to focus said laser beam on  
12          individual storage elements of said medium, and  
13          modulation means arranged to modulate said beam in  
14          accordance with the digital information to be recorded.

1       2. The system as claimed in Claim 1 wherein  
2                 said scanning means is arranged to focus said beam  
3                 successively on the individual storage elements, and  
4                 said modulation means is arranged to change the  
5                 intensity of said beam between two levels of intensity in  
6                 accordance with the information to be recorded, one of  
7                 said levels being of sufficient intensity to produce an  
8                 immediately detectable alteration of one of said storage  
9                 elements as a result of exposure to scanning by said  
10                scanning beam, and the other of said levels being of an  
11                intensity that causes no significant alteration in a  
12                storage element as a result of exposure to said laser beam  
13                during scanning.

14

15        3. The system as claimed in Claim 1 wherein  
16                said laser beam source is a diode laser.

17

18        4. The system as claimed in Claim 1 wherein  
19                each of said storage elements is a flat micromirror.

20

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1       5. The system as claimed in Claim 1 wherein  
2                said substrate is a sheet of transparent ther-  
3                moplastic having in a first surface thereof a regular  
4                array of spaced indentations, and wherein  
5                each of said storage elements is on the bottom of one  
6                of said indentations.

7  
8       6. The system as claimed in Claim 1 wherein  
9                each of said storage elements is a micromirror sup-  
10          ported by thermoplastic material and in which  
11                said alteration is the result of heat deformation of  
12                said thermoplastic material.

13  
14      7. The system as claimed in Claim 6 including  
15                a plurality of spaced, discrete projections extending  
16          from one surface of said thermoplastic material and each  
17          supporting one of said micromirrors.

18  
19      8. The system as claimed in Claim 6 wherein  
20                each of said micromirrors has a maximum surface  
21          dimension between about one and 2.5 micrometers.

22  
23      9. The system as claimed in Claim 6 wherein  
24                the reflectivity of each of said micromirrors in the  
25          unaltered state is at least 20 percent.

1       10. The system as claimed in Claim 6 wherein  
2                  each of said micromirrors comprises a metal-  
3                  containing film.

4

5       11. The system as claimed in Claim 6 wherein  
6                  said medium comprises

7                  a sheet of plastic having formed integrally  
8                  therewith a regular array of spaced mesas each supporting  
9                  one of said micromirrors, each of said micromirrors being  
10                 capable of being destroyed by a single pulse of focused  
11                 energy less than 200 nanojoules per square micrometer  
12                 thereby to become a depository for one bit of digital  
13                 information.

14

15       12. The system as claimed in Claim 6 wherein  
16                  in the unaltered state each of said micromirrors has  
17                  a reflectivity between 20 and 55 percent, and in the  
18                  altered state has a reflectivity substantially less  
19                  than in the unaltered state, the number and location of  
20                  said micromirrors having a reduced reflectivity being a  
21                  function of the digital information recorded on the  
22                  medium.

23

24

25

1       13. The system as claimed in Claim 6 wherein  
2            said micromirrors are arranged in parallel rows  
3            forming a regular array, and  
4            said scanning means is arranged to scan said rows  
5            successively in opposite directions.

6  
7       14. A system as claimed in Claim 13 wherein  
8            said scanning means is arranged to scan along  
9            parallel paths diagonal to said rows.

10  
11      15. The system as claimed in Claim 13 wherein  
12            each of said micromirrors is a metal-containing film  
13            having  
14            a reflectivity of at least 20 percent and a maximum  
15            surface dimension between about one and 2.5 micrometers.

16  
17      16. The system as claimed in Claim 15 wherein  
18            said substrate has a reference surface, and  
19            a regular array of spaced mesas extending from said  
20            surface, each supporting one of said micromirrors.

21  
22      17. The system as claimed in Claim 16 wherein  
23            said medium includes a transparent layer overlying  
24            and in intimate contact with said micromirrors.

1       18. A medium for recording digital information comprising  
2            a substrate having  
3            an array of spaced discrete storage elements,  
4            each of said storage elements being individually  
5            capable of immediately detectable alteration by exposure  
6            to a single pulse of focused energy of less than 200 nano-  
7            joules per square micrometer thereby to become a deposi-  
8            tory for one bit of digital information,  
9            the specific area of each storage element subject to  
10          such alteration by said focused energy being pre-defined  
11          prior to the exposure to such energy.

12  
13       19. The medium as claimed in Claim 18 wherein  
14            said substrate is formed of transparent material  
15            having therein a regular array of spaced depressions of  
16            uniform depths extending inwardly from one plane thereof,  
17            and  
18            each of said storage elements comprises a micromirror  
19            covering the bottom of one of said depressions.

20  
21       20. The medium as claimed in Claim 18 wherein  
22            each of said elements is a micromirror, and  
23            said micromirrors are arranged in a regular array.

24  
25

1       21. The medium as claimed in Claim 20 wherein  
2                  the minimum distance between said micromirrors is not  
3                  significantly less than the maximum surface dimension of  
4                  said micromirrors.

5

6       22. The medium as claimed in Claim 20 wherein  
7                  each of said micromirrors has an area between about  
8                  0.7 and four square micrometers.

9

10      23. The medium as claimed in Claim 20 wherein  
11                substantially all of said micromirrors in its origi-  
12                nal unaltered state has a reflectivity of at least 20% at  
13                830nm.

14

15      24. The medium as claimed in Claim 20 wherein  
16                said substrate comprises a flexible thermoplastic and  
17                including  
18                a plurality of mesas formed integrally with said  
19                substrate and each supporting one of said micromirrors,  
20                said mesas defining a plurality of valleys therebetween.

21

22      25. The medium as claimed in Claim 20 wherein  
23                each of said micromirrors is formed of a metal-con-  
24                taining film.

25

1       26. The medium as claimed in Claim 25 wherein said film  
2       is a composite of a metal and a silicate.

3

4       27. The medium as claimed in Claim 26 wherein  
5       said film is a composite of gold and silicon dioxide.

6

7       28. The medium as claimed in Claim 20 including  
8       a plurality of spaced discrete mesas extending from  
9       said reference surface, each supporting one of said micro-  
10      mirrors, and wherein  
11       each of said micromirrors is formed of a metal-  
12      containing film.

13

14      29. The medium as claimed in Claim 20 wherein  
15       each of said micromirrors has a maximum dimension no  
16      greater than about one micrometer.

17

18      30. The medium as claimed in Claim 24 wherein  
19       the reflectivity of said micromirrors in both the  
20      altered and unaltered state is greater than the reflec-  
21      tivity from said valleys.

22

23      31. The medium as claimed in Claim 29 wherein  
24       each of said micromirrors has an area no greater than  
25      about five square micrometers.

1       32. the method of recording digital information  
2           comprising the steps of  
3              providing a substrate,  
4              supporting from said substrate, discrete, spaced  
5              storage elements,  
6              each of said storage elements being capable of  
7              immediately detectable alteration by exposure to focused  
8              energy, and  
9              exposing, in accordance with digital information to  
10             be recorded, selected storage elements to a source of  
11             focused energy of sufficient intensity to produce an  
12             immediately detectable alteration in each of said selected  
13             storage elements,  
14              each of said storage elements defining, prior to  
15             exposure to said focused energy, a specific area subject  
16             to alteration thereby.  
  
17  
18        33. The method as claimed in Claim 31 wherein  
19              each of said storage elements is a micromirror and  
20              including the step of  
21              arranging said micromirrors in a plurality of spaced  
22              parallel rows.

23  
24  
25

1       34. The method as claimed in Claim 33 wherein  
2                said selected micromirrors are exposed to said  
3                focused energy successively along each of said rows, the  
4                direction of movement of said exposure being reversed on  
5                successive rows.

6  
7       35. The method as claimed in Claim 33 wherein said micro-  
8                mirrors are arranged in a substantially regular array.

9  
10      36. The method as claimed in Claim 33 wherein  
11                said exposure to said focused energy is successively  
12                along parallel paths diagonal to said rows.

13  
14      37. The method as claimed in Claim 36 including the step  
15                of  
16                supporting each of said micromirrors on a discrete  
17                mesa extending from said reference surface, each of said  
18                mesas being separated by intervening valleys from adjacent  
19                mesas.

20  
21      38. The method as claimed in Claim 37 wherein  
22                said medium is formed predominately of thermoplastic  
23                material.

1       39. The method as claimed in Claim 38 wherein  
2                said focused energy is a laser beam,  
3                and said exposure comprises the step of  
4                focusing said laser beam on said selected micro-  
5                mirrors thereby to destroy the micromirror and thereby  
6                record one bit of digital information.

7

8        40. The method of making and pretesting a digital  
9                recording medium comprising the steps of  
10                forming a substrate of thermoplastic material having  
11                thereon a regular array of spaced, separate predefined  
12                information storage areas,  
13                coating each of said areas with a reflective coating  
14                thereby to form a regular array of optically alterable  
15                micromirrors,  
16                successively scanning each of said micromirrors with  
17                a laser beam having an intensity less than that which will  
18                significantly reduce the reflectivity of said micro-  
19                mirrors, and  
20                measuring the light reflected from each micromirror  
21                and comparing it with a predetermined level of reflec-  
22                tivity thereby to detect defects in the reflectivity of  
23                said micromirrors.

1       41. The method of recording digital information  
2           comprising the steps of  
3               providing a substrate of thermoplastic material,  
4               depositing on said substrate a plurality of parallel  
5               rows of spaced, discrete, optically-alterable micro-  
6               mirrors, and

7               scanning along paths diagonal to said rows with a  
8               laser beam modulated, in accordance with digital infor-  
9               mation to be recorded, between two levels of intensity,  
10              the higher of said intensities being great enough to  
11              destroy the reflectivity of one of said micromirrors by  
12              exposure thereto during the scanning.

13  
14       42. The method of making a medium for the storage of  
15           digital data comprising the steps of  
16               providing a substrate of transparent thermoplastic  
17               material having first and second opposing surfaces,  
18               forming in said first surface a substantially regular  
19               array of spaced depressions,  
20               depositing a reflecting coating on said first surface  
21               and on the bottom of each of said depressions, and  
22               removing said reflective coating from the exposed  
23               areas of said first surface between said depressions.

24  
25

1       43. The method as claimed in Claim 42 wherein  
2                 said coating on said first surface is removed by  
3                 abrasion.

4       44. The method as claimed in Claim 42 incuding the step  
5                 of

6                 applying a non-reflecting layer to said areas of said  
7                 first surface between said depressions.

8  
9       45. A digital recording medium comprising  
10                 a transparent thermoplastic substrate having first  
11                 and second opposing surfaces,

12                 said first surface having therein a substantially  
13                 regular array of spaced depressions,  
14                 a plurality of optically-alterable micromirrors each  
15                 formed on the bottom of one of said depressions,  
16                 each of said micromirrors being capable of reflecting  
17                 at least 20 percent of laser light focused upon it through  
18                 said second surface of said substrate.

19  
20       46. The medium as claimed in Claim 45 wherein  
21                 each of said micromirrors is capable of being  
22                 destroyed by laser beam having an energy level less than  
23                 200 nanojoules.

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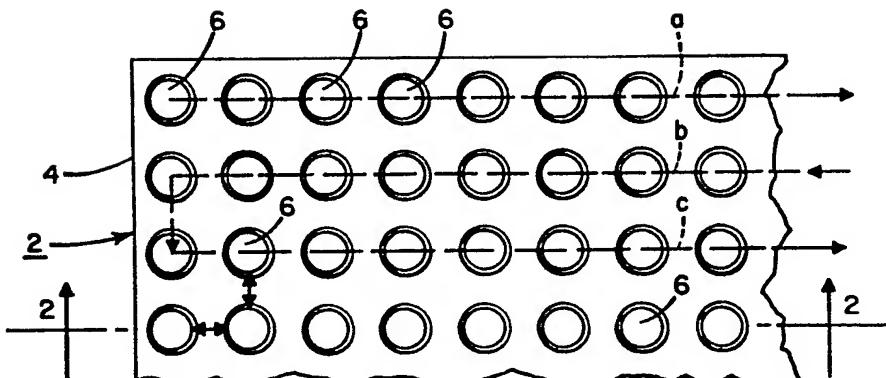


Fig. 1.

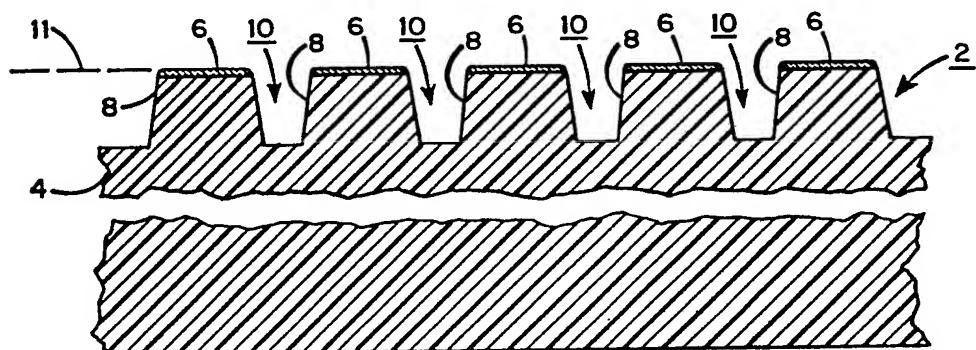


Fig. 2.

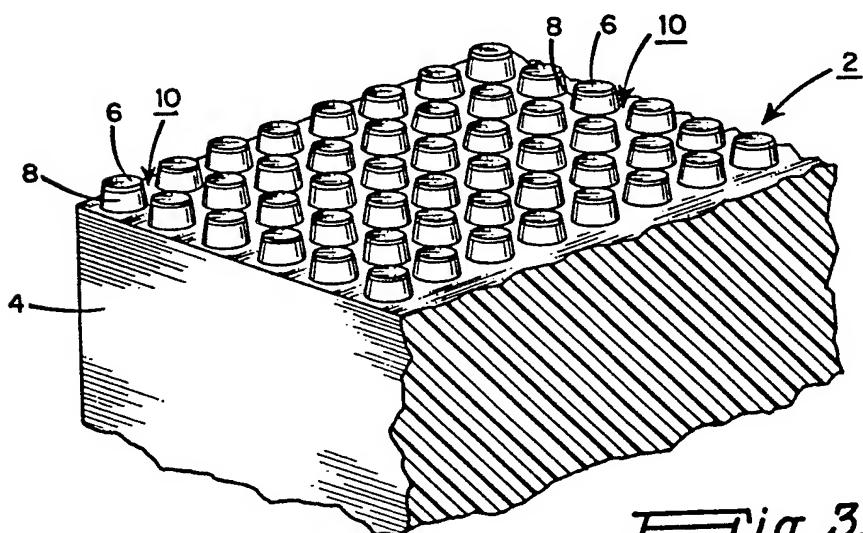


Fig. 3.

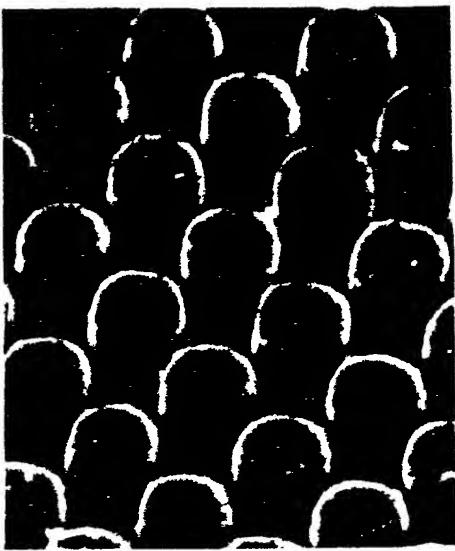


Fig. 4.



*Fig. 5.*

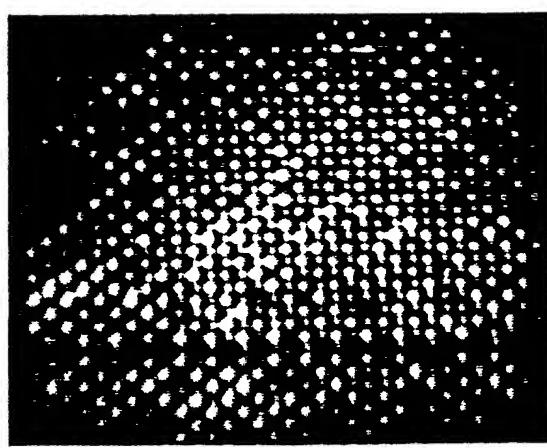


Fig. 6.

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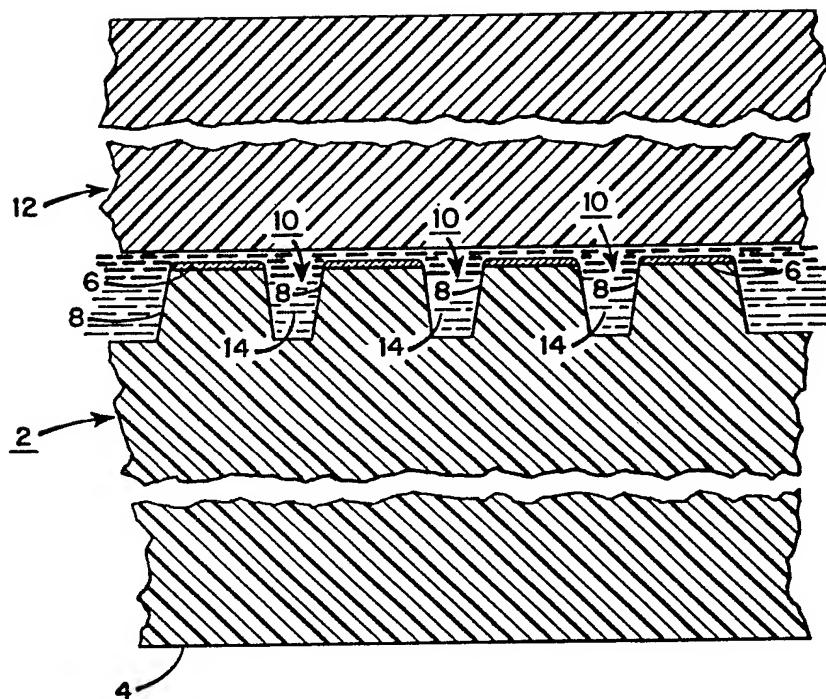


Fig. 7.

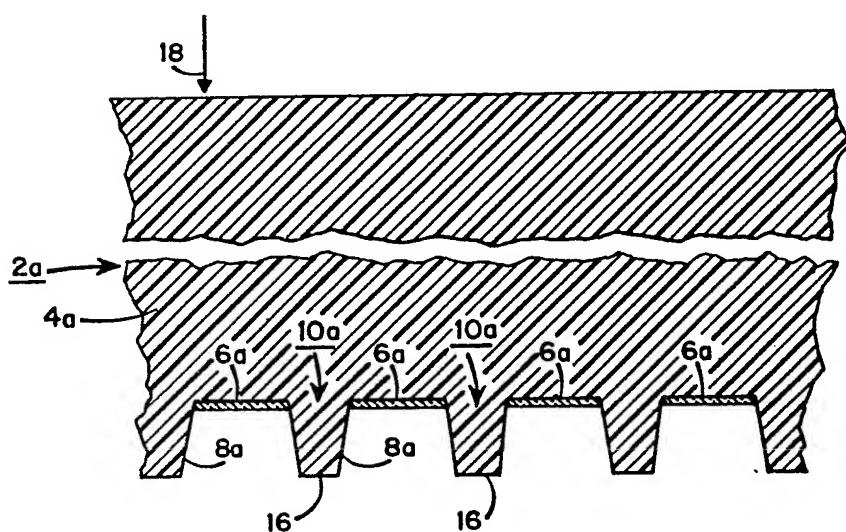


Fig. 8.

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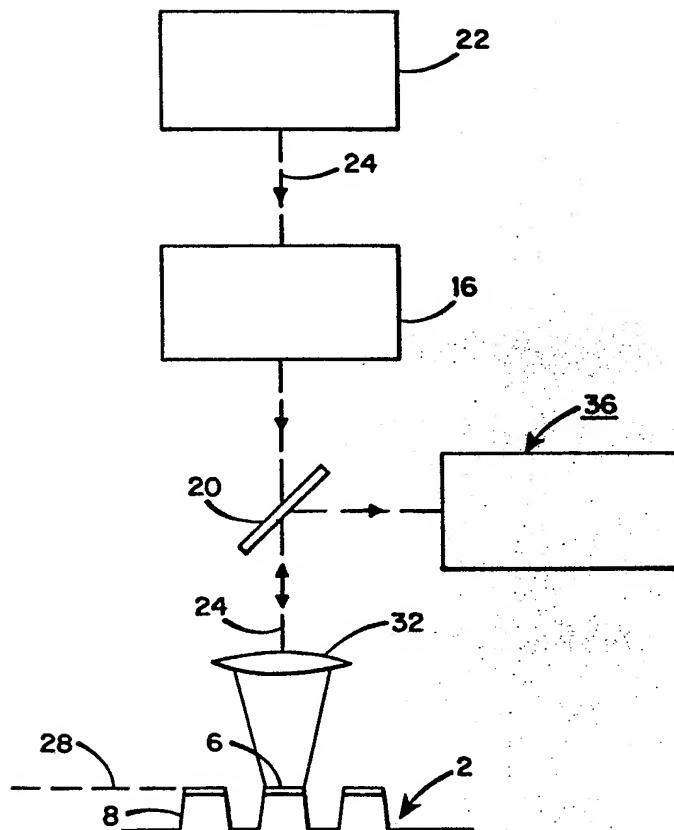


Fig. 9.

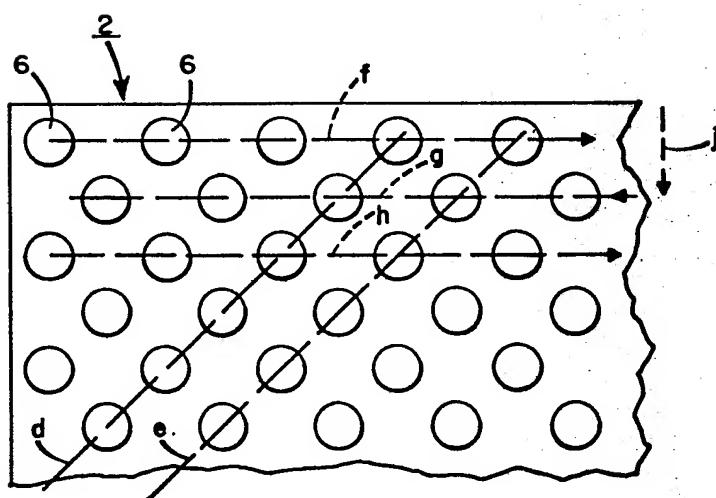


Fig. 10.

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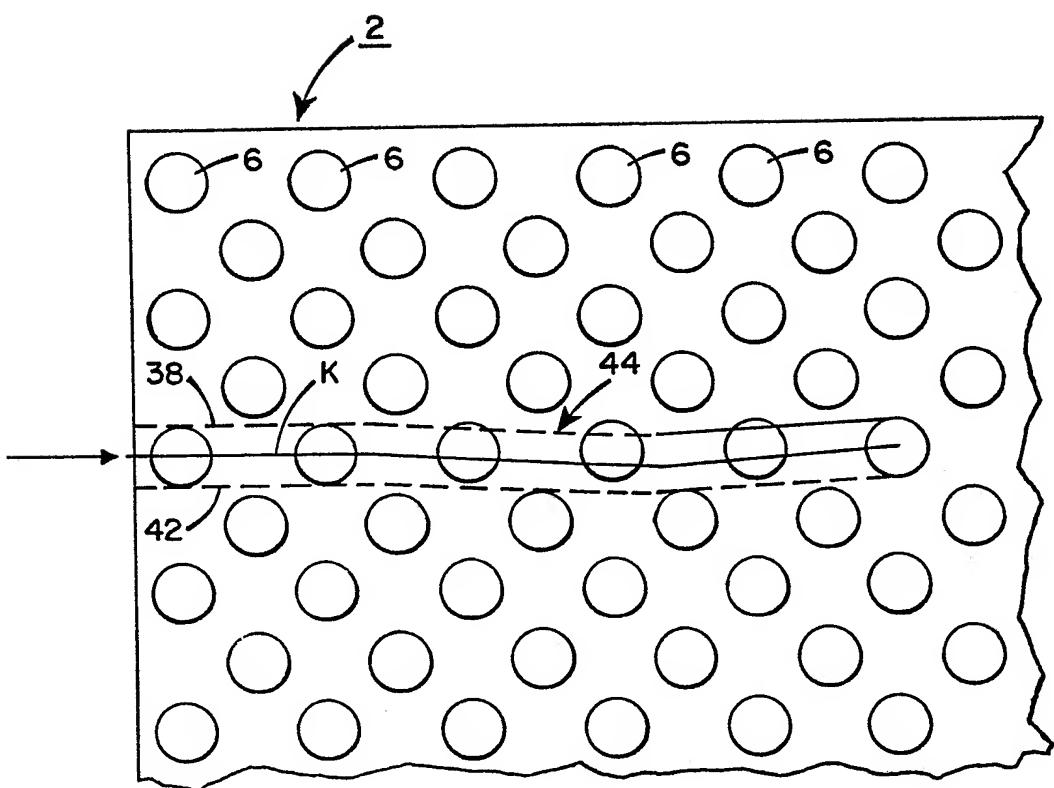


Fig. 11.